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21.5: Dynamic Properties of Individual Carbon Nanotube Emitters for Maskless Lithography

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The stable chemical structure, high current density, and low turn-on fields of carbon nanotubes make them highly attractive for cold field emission applications [1]. The individual CNT's low electron beam energy spread and high brightness values make it particularly desirable for advanced applications such as electron microscopy and electron beam lithography at 20-nm and below critical dimension regime. A fundamental understanding of the individual carbon nanotube electron source is essential for implementation of such applications. We previously demonstrated an improved fabrication technique for individual CNT emitters based on MEMS technology [2]. Also, our group presented an experimental and simulation investigation of the influence of cathode support structure geometry on the field emission properties of a single CNT emitter [3]. In this paper, we present an empirical study of dynamic behavior of an electron source system which incorporates an individual CNT. We propose a representative circuit model that is simple yet particularly valuable for emission current control for each CNT emitter in an array to facilitate high throughput maskless lithography.

Figure 1 shows SEM images of a typical individual MWNT attached to a nickel-coated silicon microstructure utilized in this study. In each field emission experiment, the CNT cathode and a cylindrical planar gold anode were separated by a distance d in a diode configuration, as illustrated in Fig. 2(a), at a base pressure of 10^{-8} Torr. As shown schematically in Fig. 2(b), we propose a diode circuit model consisting of a capacitor in parallel with a voltage-controlled variable resistor for the CNT electron source system. The resistor R is governed by the current-voltage characteristics of the field emitter, as described by Fowler-Nordheim theory [4]:

$$R = \frac{V_{applied}}{2\pi r^2 A\left(\beta V_{applied}\right)^2} \exp\left(\frac{B}{\beta V_{applied}}\right) \qquad (1)$$

where $V_{applied}$ is the voltage applied across the diode, β is the field enhancement factor, r is the radius of the field emitting area, and A and B are constants. The capacitance C of the diode model is predominantly characterized by capacitance between the cathode holder and the anode block due to the significantly smaller dimensions of the CNT tip and its support structure.

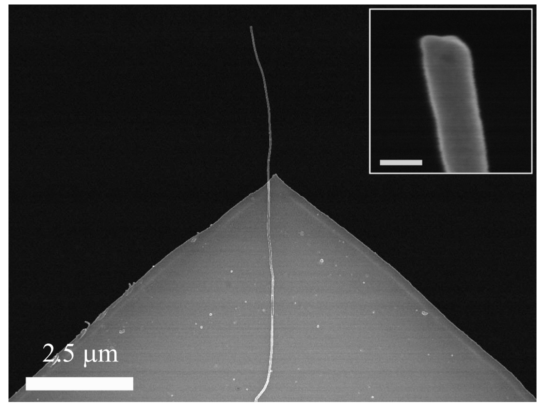

Figure 1. SEM images of CNT cathode and its CNT emitter tip (inset, scale bar 50 nm).

Figure 3 shows experimental diode transient current responses for different applied input step voltages that range from 20 V to 240 V for d = 74 µm. The turn-on voltage, V_{on}, required to achieve 1-nA emission current, is 140 V. At an applied voltage of 20 V, below V_{on}, the nanotube loop is effectively open and the circuit response is consistent with a discharging capacitor. However, at 180 V applied, above V_{on}, the nanotube loop conducts and thus the capacitor discharges through the nanotube loop as well. It is also interesting to note in Fig. 3 that the discharging stages converge for the cases where the applied step input is above V_{on}. This occurs because for each of these cases, the field emission current shuts off when the applied voltage falls below the same field emission threshold voltage. The same trend was observed in the transient responses for d = 10 µm and 138 µm.

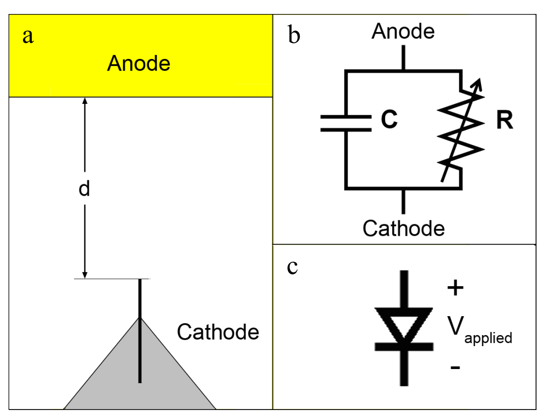

Figure 2. (a) Experimental diode.(b) Diode circuit model. (c) Symbol to represent diode.

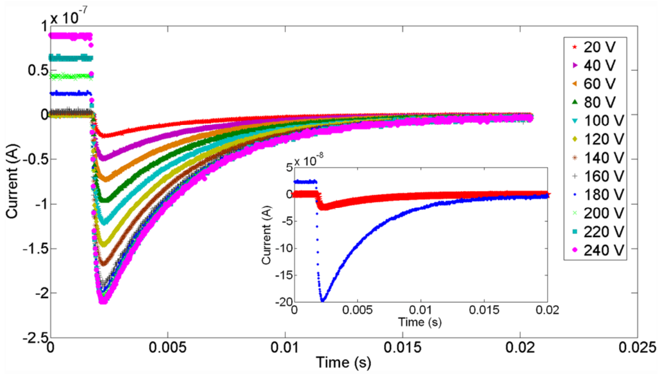

Figure 3. Transient responses for various falling input steps for d = 74 μm. Inset, 20 V (red stars) and 180 V (blue dots).

Figure 4 shows field emission current versus applied voltage (I-V) data collected for these three cathode to anode separations. The corresponding resistance versus voltage (R-V) data explains the dynamic transient responses. Below turn-on voltage, the diode behaves as an open circuit (4 TΩ at the ammeter noise floor). Above turn-on voltage, resistance falls exponentially. This dynamic behavior demonstrates the validity of the diode circuit model given in Fig. 2.

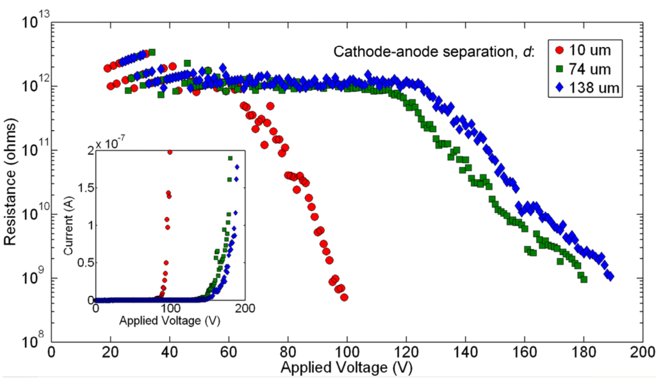

Figure 4. I-V and R-V for cathode in Fig. 1 for varying cathode to anode separations, *d*.

The model's significance is revealed by investigating each CNT emitter in an array. As shown in Fig. 5(a), an individual MWNT was attached asymmetrically to the left side of a nickel-coated silicon microstructure. As shown in Fig. 6, the field emission I-V data was collected for d = 10 μm. The turn-on voltage for the nanotube, which measured 1.5 μm from the edge of the microstructure to its tip, was 109 V. A second MWNT was attached 16 μm away from the first on the right side of the same microstructure, as shown in Fig. 5(b). After shortening this nanotube to the same length as the first, field emission data was collected under the same conditions and plotted in Fig. 6. The turn-on voltage for this structure was 26 V, significantly lower than that of the isolated emitter. Finite element analysis utilizing Technology Computer Aided Design and analytical

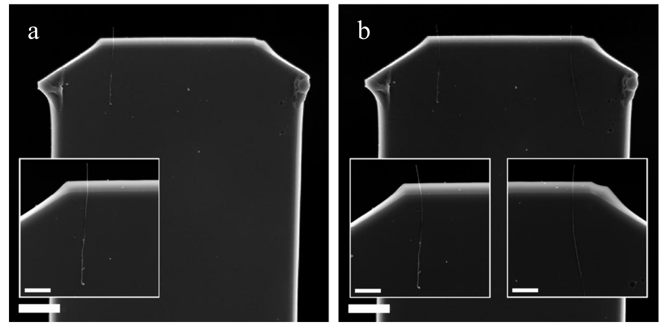

Figure 5. (a) SEM images of single MWNT attached to left side of Ni-coated Si microstructure. (b) SEM images of a second MWNT attached to the right side. Main scale bars 5 μm, insets 2 μm.

reasoning proves that the greatly improved field emission data can only be attributed to the second emitter alone rather than to both emitters operating simultaneously.

Presently the nanoscale CNT tip geometry is not precisely controllable and thus the diode circuit model is indispensable for CNT emitter array applications. The differences in the nanoscale tip structure from one CNT to another leads to unfavorable disparity in field emission characteristics. This disparity can be regulated by determining the R-V characteristics of each emitter. Therefore, the diode circuit model must be employed to individually manage each CNT emitter in an array for high-throughput parallel e-beam lithography in which precise dose control is imperative.

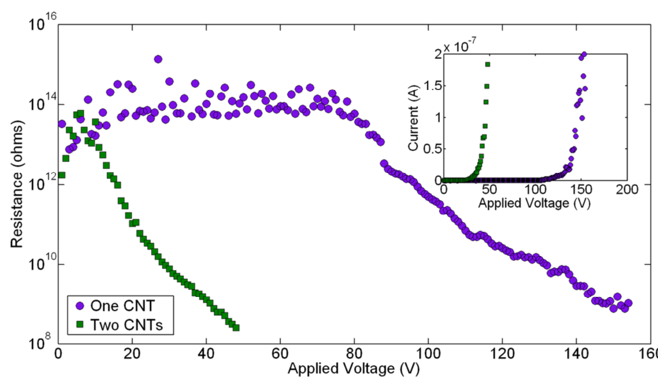

Figure 6. I-V and R-V for cathodes in Fig. 5.

References

1. Meyyappan, M., *Carbon Nanotubes: Science and Applications*, 1st ed. Boca Raton: CRC, 2004.
2. Ribaya, B.P., J. Leung, P. Brown, M. Rahman, and C.V. Nguyen, *Nanotechnology*, publication pending.
3. Niemann, D.L., B.P. Ribaya, N. Gunther, M. Rahman, J. Leung, and C.V. Nguyen, *Nanotechnology*, 18, 485702, 2007.
4. Fowler, R. H., L. Nordheim, *Proc Royal Soc London A*, 119, 173, 1928.